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Magnetomechanical training of single crystalline Ni–Mn–Ga alloy

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ABSTRACT

A 5M Ni–Mn–Ga single crystal was investigated, supplied by Adaptamat Ltd, Finland. Especially low temperature magnetic actuation as well as cyclic tensile-compression tests revealed promising properties, which provide useful insights for training concepts in polycrystalline materials. Successive compressions lead to a significant reduction of the twinning stress by a factor of two.

1. Introduction

Ni–Mn–Ga shape memory ferromagnets exhibit large strain in a magnetic field due to twin boundary motion. Since the discovery of this effect in 1996 by Ullakko et al. no other material could show the performance of Ni–Mn–Ga single crystals, especially at room temperature [1]. Therefore, single crystal materials are still necessary to investigate the principle properties of this alloy in order to develop a preparation route for polycrystalline magnetically active materials.

The magnetic actuation is governed by the magnetocrystalline anisotropy of the material, its magnetisation and the stress, under which twin boundaries move, hereafter referred to as twinning stress. The magnetic properties, especially magnetocrystalline anisotropy and saturation magnetisation are defined by the crystal structure (5M, 7M, NM martensite or austenite), regardless of the history of the sample. Therefore these data can be taken from literature easily [2,3]. The twinning stress and the mechanics of twin boundary motion have been investigated, especially by Müllner et al. [4,5]. As the twinning stress is determined by the way a twin boundary interacts with possible defects in the crystal, this interaction is of vital interest [6]. Especially if a twin boundary passes a certain area or the whole crystal several times, it has to be clarified, if the twinning stress rises (work hardening), lowers or remains unchanged.

In the last years, several reports were published about training of Ni–Mn–Ga single crystals. In our previous report both the increase of strain from 2% to 8% and a significant decrease of twinning stress from 60 MPa to 15 MPa are observed in polycrystals [7]. Straka et al. reported on mechanical training in single crystals. For both 7M and 5M structure the twinning stress could be suppressed down to about 1 MPa, thus allowing for magnetically resetting the samples [8]. Molnar et al. monitored the crystallographic reorientation during the mechanical training by neutron diffraction [9]. They also observed a decrease of twinning stress, especially the initial peak was no longer visible after training. Chmielus et al. found an effect of surface roughness. Mechanically polished or electropolished samples were found to have a lower twinning stress than non-polished samples in addition to the reduction of twinning stress over the cycle number [10]. Due to the initial status of the sample the twinning stress could be suppressed to only 10% of the initial value. The largest effect is found after the first compression, when the sample is detwinned for the first time. Correspondingly, the twinning stress increases when the surface roughness is increased by mechanical grinding [11]. Müllner et al. observed an effect during training in a rotating magnetic field [5]. The results of our thermomagnetic training are published elsewhere [12]. This article deals with the magnetomechanical training of an already magnetically active sample. Secondly, the consequences of a push–pull training concept are revealed. Finally the low-temperature actuation properties of the single crystal are measured down to $T = -25$ °C.

2. Experimental

Two main approaches of cyclic deformation are investigated in this article. The first approach only works for materials that already show magnetic field induced strain and consists of a magnetomechanical cycle. This experiment was performed in a modified mechanical

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testing machine INSTRON 8502. During these cycles the sample is compressed at first and after that an external magnetic field is applied perpendicular to the former load direction allowing the sample to elongate in that direction with the pistons of the testing machine being driven apart. This approach has also been chosen by Aaltio et al. [13]. The systematical error of the strain was about 0.01 mm, corresponding to 0.05% of strain. The error of the stress can be taken from the rather large noise in the figures, since a 5 kN-load cell was used. The applied magnetic field was $\mu_0H=0.7$ T. The longest axis of the crystal was named $z=20$ mm, the shortest axis was $x=3.2$ mm, the intermediate axis was $y=5$ mm. The crystal was a sample of Adaptamat, Ltd. Its structure was 5 M at room temperature, the transformation temperature was 46 °C and the composition $Ni_{49.6}Mn_{29.6}Ga_{21.2}$ in atomic per cent by EDS. The strain was measured by the motion of the cross head of the machine. The second approach is a purely mechanical pull–push deformation in a mechanical testing machine INSTRON 8562. The sample was glued on both sides to the rods of the machine equipped with a 1000 N load cell. The strain was directly measured on the sample by a clip-on strain gauge (gauge length: 10 mm). The sample was cyclically loaded to $\sigma_{max}=3$ MPa in tension as well as in compression. The strain is always measured parallel to the load direction.

3. Results

Since the single crystal was already magnetically active in the as-received state, a magnetomechanical cycling could be applied. The sample was compressed along the z-axis. Since twin boundaries were visible on the y–z plane with roughly a 45° angle to the edges of the sample, the magnetic field was applied along the y-axis. This caused full strain recovery during unloading the sample to zero. Before the application of the magnetic field the sample was unloaded to 4 N, being 0.25 MPa. After that the field was applied and the pistons of the testing machine were driven apart, so that the full stress–strain characteristics of the elongation process could be obtained by recording the force the sample exerts on the pistons over the whole expansion range. This cycling was done 8 times with a considerable lowering of the twinning stress being observed. The stress decreased from 1.2 MPa in the beginning (“1” in Fig. 1) to 0.5 MPa in the 8th cycle. Especially the initial maximum is no longer visible in the last cycle.

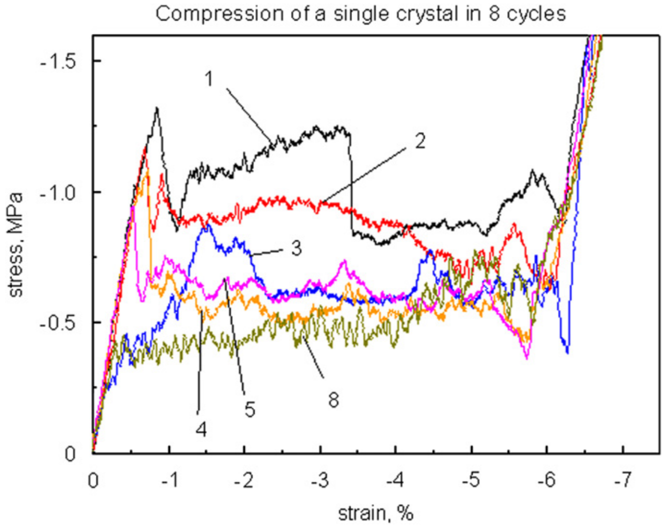

Fig. 1. Cyclic compression of a single crystalline Ni–Mn–Ga sample supplied by Adaptamat Ltd. The numbers in the figure correspond to the cycle number. The strain was restored after every compression in a magnetic field of 0.7 T. The maximum load was 6 MPa. The compression and relaxation was done with a cross head speed of 0.1 mm/min, which is corresponding to a strain rate of $8.33\times10^{-5}\,s^{-1}$.

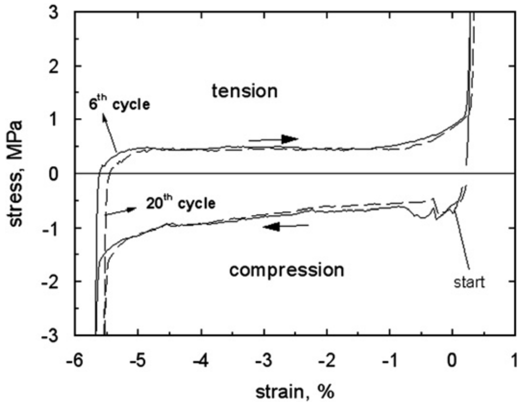

Fig. 2. Cyclic compression–tension training of the same single crystalline sample. A considerable difference can be seen in the height and shape of the stress plateaus. Since all the cycles looked very similar only the 6th and 20th cycles are shown exemplarily. A decrease of strain can be seen comparing the regions between 5% and 6% strain.

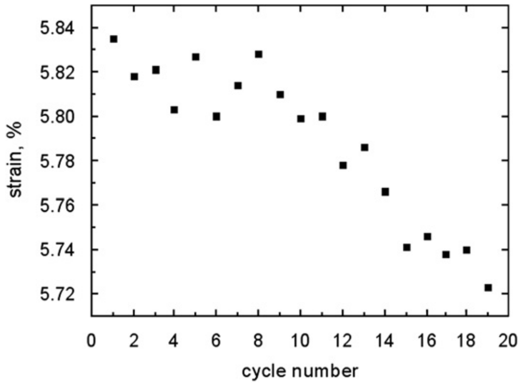

Fig. 3. Cyclic push–pull experiment. The strain decreases slowly over the cycle number. The cross head speed was 0.1 mm/min.

In order to investigate the training behaviour further the second approach was conducted, the tension–compression experiment. The results of the 6th and 20th cycle are shown in Fig. 2 exemplarily. It can be seen that the levels of the stress plateaus in compression and tension are different from each other. The stress for tension is with 0.5 MPa almost equal to the stress needed for compression after the 8th cycle of the previous test. In compression the plateau also starts at roughly 0.5 MPa, but then the stress steadily increases to almost 1.0 MPa at the end to the plateau. However, it could be shown that the strain can be almost fully reset by applying a tensile stress after the compression test.

The sample was investigated for 20 cycles in total. The total strain difference at zero stress is plotted for every cycle in Fig. 3. The strain slowly decreases with each cycle. That is why this cycling was stopped after 20 cycles.

The crystal was further investigated at lower temperatures according to the first experiment, i.e. it was compressed mechanically and the original shape was recovered in a magnetic field, with the extension process being recorded and displayed in Fig. 4. No general trend can be seen as a function of temperature. At all investigated temperatures the strain by mechanical compression could be fully recovered in an external applied field. The shape of the curve differs but the actuation stress decreases from 2.0 to 1.0 MPa with the expansion of the crystal. This stress is the difference between magnetic stress and twinning stresses. The